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LUCIA – A Tool for Land Use Change Impact Analysis

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Abstract. Land use and land cover changes have significant impact on the environment and accordingly this topic has gained increasing political awareness during the last decade. Using modelling and simulation, we can increase our understanding of the land-use system and reduce uncertainty concerning decisions. The current paper describes the development of a grid based land-use simulation model – LUCIA - facilitating the decision-making process through an adaptive and transparent modelling system. Accordingly, user friendliness and processing speed have been given top priority in the design and implementation of the system.

1 Introduction

Land use and land cover changes have significant impact on the environment and accordingly this topic has gained increasing political awareness during the last decade. Thus the European Union has carried out two land cover mapping projects (CORINE) in the years 1990 and 2000. Besides a CORINE-2006 land cover mapping is currently under construction.. Spatial planning can be used as an instrument to coordinate socio-economic development by preventing environmental problems and simultaneously protecting the natural environment and the cultural environment. Furthermore, EU has agreed on two initiatives on spatial development and planning. ESDP - the European Spatial Development Perspective [1] deals with the general principles for land use changes, whereas the Recommendation on Integrated Coastal Zone Management [2] focuses on the development of the European coastal zones. The challenge for planning is to ensure the efficient use of limited land resources and to contribute to balanced regional business development and balanced use of resources, including natural and landscape resources, soil, water and air. This can be accomplished through for example involving all stakeholders and politicians from an early stage in the planning process, and by developing tools for assessing the consequences for various planning initiatives – here under setting up scenarios for finding the best balance between different interests.

Using modelling and simulation, we can reduce uncertainty and increase our understanding of the land-use system. Spatial planning is a future-oriented activity, strongly conditioned by the past and present, and the planners need to enhance their analytical, problem solving and decision making capabilities. With the help of land-use models, it can facilitate scenario building and provide an important aid in the decision making process. During the last few years several land-use modelling systems have been developed, but the models are not available for general use.

The aim with the current project has been to develop a land-use simulation model facilitating the decision process including the public participation phase concerning regional development plans – particularly in the coastal zone. Consequently, the model needs to be adaptive and extensible to include changes required by the spatial planners, the local politicians and the wide range of stakeholders. Furthermore it must be easy to explain the model and how the results are the outcome of the various driving forces

The paper is divided into 5 parts. After the introduction follows a discussion of land-use modelling and a conceptual description of the current model. Then in the next section follows a description of the implementation and calibration of the model. To illustrate the potential use of the model the next-to-last section presents some example scenarios. The paper ends with some conclusions and an outline for subsequent work.

2 Land-use dynamics and modelling

Land-use changes are complex interactions between the human society and the bio-physical environment, and setting up a reliable model is a huge challenge. Models of land-use change can address two separate questions: a) where are land-use changes likely to take place – i.e. the location of change; b) and at what rates are changes likely to progress – i.e. the quantity of change [3]. A prerequisite to the development of realistic land-use simulation models is the identification of the most important drivers of change, and how to represent these drivers in a model. The determinants of land-use change can be divided into two main categories: a) the bio-physical drivers, and b) the socio-economic drivers. The bio-physical drivers consist of various characteristics and processes concerning the natural environment such as: topography, soil types, drainage patterns, climate and availability of natural resources. Usually, the bio-physical drivers do not cause land-use change. However they do cause land cover change, which subsequently may affect land-use decisions. The socio-economic drivers comprise factors such as: population change, industrial structure, economic development, technological change, policies and legislation, spatial interaction, etc.

2.1 Model definition

Basically the current model simulates future land-use patterns based on socio-economic drivers at two distinct levels [4], and the land-use types are divided into three categories, similarly to for example the MOLAND model [5] [6]. The most important category is the active land-use types, which are forced by the demands generated externally. Another category is the passive land-use types, which are not driven by an external demand, but on the other hand enter into the calculations, because they can disappear by being transformed into one of the active land-uses. The final category is the static land-uses, which cannot be transformed into one of the active land-uses, but will nevertheless affect the land-use simulation by attracting or repelling land-use transformation within their vicinity.

The overriding driving forces are basically population growth and economic growth. However, in the current project related to the coastal zone particular emphasis must be put on growth in recreational activities – particularly the expansion of summer cottage areas. These drivers represent what we call macro-level drivers, and they are modelled externally to our model in various sector models, and basically define the demand for land from each active land-use type.

At the micro level, we deal with drivers often used in various land-use modelling efforts. The first element to consider is obviously the *suitability* of each grid cell – i.e. how the specific characteristics of each cell can support a given land-use. The next element to consider is *accessibility* – i.e. access to the transportation network. Some activities like shopping require better accessibility than for example recreational activities. Often the latter activity even feels attracted to areas with low accessibility due to for example lower noise levels in such areas. The third element to involve in the model is the neighbouring effect, which represents the attractive or repulsive effects of various land-uses within the neighbourhood. It is generally well known that some land-use types for example private service (shopping) tends to cluster, whereas others – e.g. recreation and industry tend to repel each other. However cells, which are more remote, will have a smaller effect. Within the model we refer to this effect by the term *proximity*. The fourth micro level driver for urban development can be summarised in the term *attractiveness*. Generally, bigger cities are considered more attractive due to the wide supply of services and jobs, but even within cities some neighbourhoods are considered more attractive than others, and this kind of attractiveness can even change over time. These four headline factors – suitability, accessibility, proximity and attractiveness - define the basic preconditions for the cells ability to support a given land-use, and are in some degree fixed, although the accessibility can be changed by for example improving the infrastructure. Policy making at national and local level have a strong influence on land-use – particularly policies that have a spatial manifestation like creation of conservation areas or designation of areas for subsidised development [7]. However even more general legislation like the EU Common Agricultural Policy has a strong indirect influence on the spatial development in the rural areas. However, the current version of the model does only involve policies and legislation with an explicit spatial aim under the headline *Zoning*. Based on these principles we can set up a conceptual model for our land-use simulation model.

The current model applies a cell-based modelling technique, relying on the general principles for multi-criteria evaluation, whereas the native CA approach is disregarded. The transition potential is calculated in two steps. First by combining the factors in the form of a weighted linear combination, and next the constraints, consisting of Boolean maps only containing excluded and permitted areas, are created and multiplied with the factor expression.

$$P^L(t+1) = C^L_1(t) * C^L_2 * \dots * C^L_n * \sum (w^L_i * F^L_i)$$

where

P = Transition potential

C = Constraints (0 or 1)

F = Factors (values between 0.0 and 1.0)

w = individual weight factor between 0 and 1

L = land-use type

The model can easily be adapted and extended by adding more factors or constraints. Initially w is set to 1.0 for all factors, but during calibration the value of w can be lowered to obtain a better agreement between the simulated land use and the real land-use for historical years.

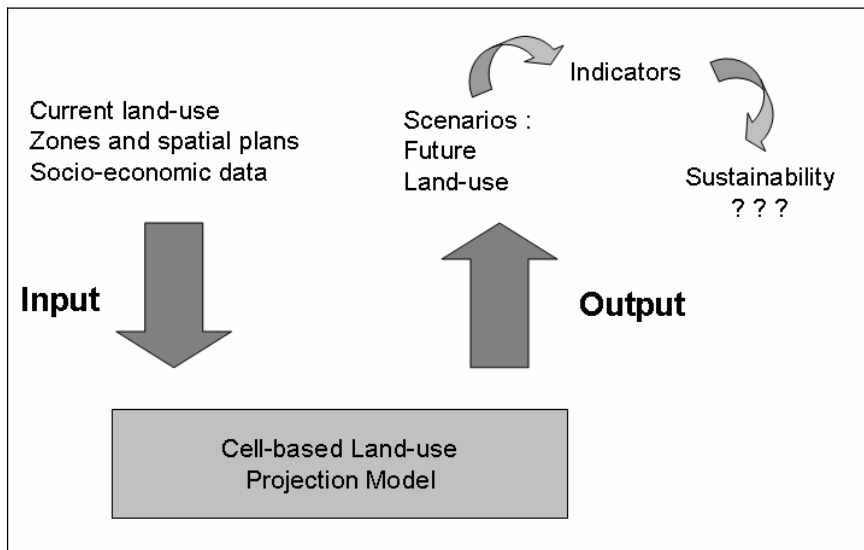


Figure 1. Principles of the LUCIA land-use simulation model.

The factors (Suitability, Accessibility, Proximity and Attractiveness) have dimensionless values between 0.0 and 1.0, whereas the constraints (Zoning) have binary values – 0 or 1. By combining the factors and constraints for each active land-use type (L), we can estimate for each cell the transition potential (P) for changing the land-use from one type to another. Additionally, we need to incorporate the spatial distribution of the socio-economic drivers. The number of cell values to be changed

during the iterations is determined by the external drivers. Once the transition potential has been calculated for all active land-uses the cell transformation process can start. The cell changes starts with the cell having the highest transition potential and this process proceeds downwards until the predetermined number of cell changes for each active land-use category has been reached. This way of doing is in accordance with von Thünen's assumption, that (in equilibrium) land is devoted to the use that generates the highest potential profitability [7].

2.2 The macro level driver data

The socio-economic drivers at the macro level (regional level) comprise factors such as: population change, industrial structure, economic development, technological change, policies and legislation. However, these conceptual drivers must be converted into demand for land for all the active land-use types, and this process is not straightforward at all. Generally we will expect that a growing population will increase the demand for residential purposes, and this is usually correct. But what about a static and even declining population – will this situation free cells from residential to other purposes? Not necessarily. Within the case area the number of people fell marginally from 134447 to 134228, but nevertheless the number of cells with residential land-use increased with 30 cells from 7693 to 7723! This reflects the so-called thinning out effect, where each dwelling unit houses fewer and fewer people.

Thus the demand for more space for residential purposes should not only consider population growth but also this thinning out effect. Similarly, the relationships between economic growth and the demand for land for industry and service facilities are not easy to resolve. The economic growth will normally require bigger factories, but often the production processes become more effective, or the factory moves from a central location (often near the harbour) to a new location at the urban fringe and near motorway junctions. This requires new space for industrial purposes, but at the same time frees their original central location for other purposes – often residential. A parallel process can be observed for many service facilities. The economic growth in the current study is based on the regional economic growth index from Denmark Statistics. It is available from 1993 and forward. The index figures for 1990 – 1992 are estimated from linear extrapolation.

3 Implementation

Cellular automata (CA) is an obvious way to take spatial interaction into account and CA based models have been a very popular way of implementing dynamic land-use models. Basically, cellular automata models determine the number of cells to be changed in the next time step endogenously based on the transition rules defined. However the pure CA approach is not appropriate for land-use simulation, and therefore more recent CA models are based on constraint cellular automata being driven by external forces [8], [9].

The current model applies a cell-based modelling technique, but the native CA approach is disregarded. The transition potential is calculated in two steps. First by combining the factors in the form of a weighted linear combination, and next the constraints, consisting of Boolean maps only containing excluded and permitted areas, are created and multiplied with the factor expression. The proximity effect is calculated using a circular neighbourhood of 1000 meter.

An earlier version of the model [4] was implemented in ArcGIS Spatial Analyst 9.2 using Map Algebra and the Python scripting language. Although this model was appealing due to the adaptability and transparency of the model, one serious bottleneck was the really slow simulation performance. However using land-use simulations in an operational context with decision makers and probably even stakeholders requires high speed simulations. Therefore the simulation environment is separated from the GIS software and a modelling application is developed. This new so-called LUCIA (Land Use Change Impact Analysis) is developed using the Delphi 7 development suite. The simulation speed is strongly improved. The execution time is reduced with 98 – 99% compared with the ArcGIS solution! Before being used in LUCIA the original raster data sets has to be converted to ASCII raster format. The current implementation of LUCIA uses a format which is similar to ASCII rasters exported from ArcGIS Spatial Analyst. This format facilitates the import and export of data between LUCIA and one of the most used commercial raster analysis and modelling packages.

LUCIA is a complete user friendly framework for doing land use change impact analysis by organising data into projects each containing several alternate scenarios corresponding to different socio-economic drivers and planning regulations. The user interface facilitates the comparison of the alternatives, and a general impression of the GUI can be obtained from figure 2.

The application have facilities for model validation using various Kappa statistics [10], several analysis tasks supporting the calculation of different spatial indicators – like cross tabulation, zone analysis, cross classification map, distance analysis, and fragmentation index.

Finally, LUCIA has multiple visualisation possibilities for comparing the land-use of two different years, comparing two land-use scenarios and showing and animation of simulated land-use scenarios. The animation can be controlled by the user, who can start, pause, stop and zoom the animation. The animation facility is furthermore equipped with the possibility to define the animation speed. This visualisation and mapping part is developed using the CartoVCL component library (<http://www.cartoworld.com/cartovcl.htm>) facilitating the management and visualisation of ESRI shape-files, MapInfo MIF and raster images. The visualisation part in LUCIA is mainly based on the raster component.

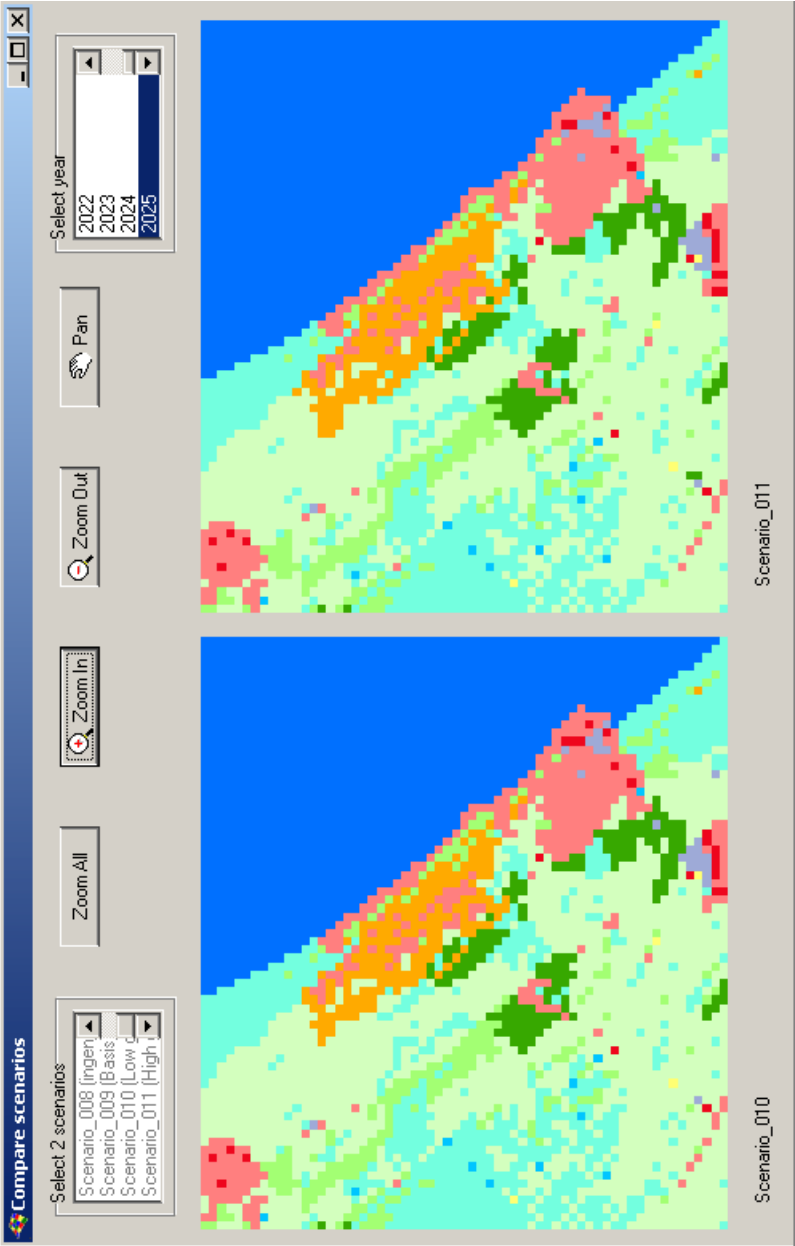


Figure 2. The Graphical User Interface of LUCIA.

4 Results

The model is tested in the Northern most part of Denmark and contains 594883 grid cells, and using a powerful PC it takes about ten seconds per year to calculate a land-use simulation, and this speed is really fast. Before doing any simulation of future land-use patterns, the validation of the model has to be checked. This is done through the calibration process. After this validation has been carried out satisfactory, we can use the model for simulating future land-use patterns based on prescribed driving forces at the macro level, and defined spatial zoning at the micro level. However, we should keep in mind that the result can only be considered reliable, if future land-use changes are determined by the same processes as the calibration period.

4.1 Calibration

Having developed the land-use simulation model, the next step is to calibrate the model in order to make the model trustworthy. Validating land-use simulation models is most often done by comparing model results for a historic period with the actual land-use changes, which have taken place within this period. The calibration period must be long enough to the underlying processes in the system having time to manifest them in a representative way. To do this we need land-use maps with some years between and the corresponding drivers for the same year span. However, the calibration period is often limited by the availability of data. Concerning detailed land-use maps we have Corine land cover for the years 1990 and 2000, whereas the land-use data for built-up areas are available through the Building and Housing register from the late seventies and onward.

According to the Building and Housing register, 3077 new buildings were built in the period from 1991 to 2000, but only 1450 of these new buildings were built outside existing built-up areas represented by 100-meter grid cells. Following the criteria for defining built-up areas the new buildings created 30 new residential cells, 33 new industry cells, 30 new service cells and 87 new summerhouse cells. The declining land-use categories were recreation with 98 cells, arable land with 20 cells, and semi-nature with 49 cells. However these are net numbers covering up transformation between the active land-use types.

During the same period the population figures for the case area *decreased* from 137158 to 136521. The case area is formed by three new municipalities (Hjørring, Frederikshavn and Læsø), and the population in Hjørring increased from 67405 in 1990 to 68479 in 2000. Consequently the population has fallen substantially for the two other municipalities. The population in Frederikshavn fell from 67241 in 1990 to 65749 in 2000. For Læsø, which is an island the situation has been negative for several years, and for the calibration period the population fell from 2512 to 2293 – corresponding to nearly 9%!

The number of cells changed during the calibration period is in accordance with the observed number. This is not surprising because the quantification of the demands for land for the various active land-use types is defined to be in accordance with the observed development. The spatial distribution of the simulated land-use changes does not reflect the observed patterns for the calibration period. A better result is obtained through trial and error processing, where we adjusted the weights for most factors. Visual inspection reveals many similarities between the simulated land-use pattern for year 2000 and the real land-use pattern, and the Kappa index varies between 0.84 and 0.77 for different simulations. You will never be able to simulate a true land-use pattern, but the purpose with the calibration process is to make a simulation having the same properties and overall land-use pattern as the calibration year.

4.2 Example scenario

The world is full of uncertainty, and the dynamic processes of land-use are interdependent and complex. It is possible, however, to make statements about the expected outcomes with a reasonable level of certainty. Scenario testing can bring the complexity into focus and provide a better knowledge base for decisions. Scenarios can also help to incorporate a long-term view and to illustrate and explain issues to stakeholders and the general public during the planning process. Below the LUCIA modelling framework is illustrated by a 20 years land-use simulation for Northern Jutland.

The Danish Government decided to expand the summer cottage zone – giving room for between 6000 and 8000 new summer cottages. This decision has been rather controversial, due to concern for the nature and environment. However, the decision is taken and the new zones defined. We have then set up two scenarios for future land-use changes in the light of the new expanded summer cottage zones. The simulation period is 2005 to 2025. The first (base) scenario is based on the following assumptions: population development as defined by Denmark Statistics, regional economic growth as defined by Denmark Statistics and a development in the number of summer cottages as an average of the period 1990 – 2005. Additionally, the new summer cottage zones have been added.

Besides to the Government has decided to double the Danish forest area during the coming 50 years. The aim of the Danish afforestation programme is to increase its share of the total land area from about 11% to 20-25 percent during the next 80-100 years. The Danish Parliament set up this goal in 1989. According to the National Afforestation Programme the new forests shall contribute to protect the ground water, increase the biodiversity, reduce the greenhouse effect, and support outdoor life, besides the ordinary production of tree.

Doubling the forest during the next 80 – 100 years requires a large effort. Within the case area in Northern Jutland the forest area amounted to 1206 hectares in 1990. This figure corresponds to 1206 100-metre cells. Using 80 years as the doubling time will require that 15 hectares of land will be converted every year – in average.

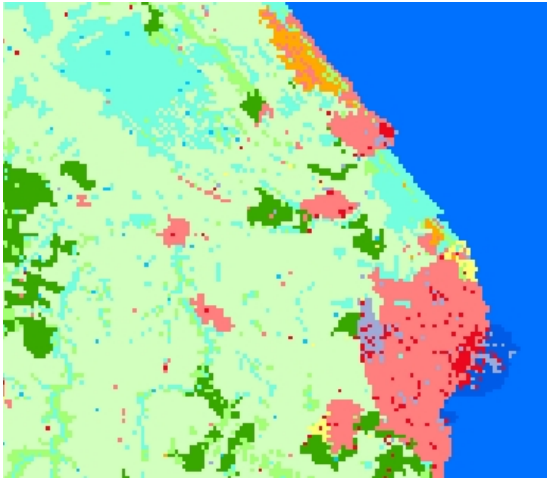


Figure 3. Land-use (monitored) in part of Northern Jutland in 2005.

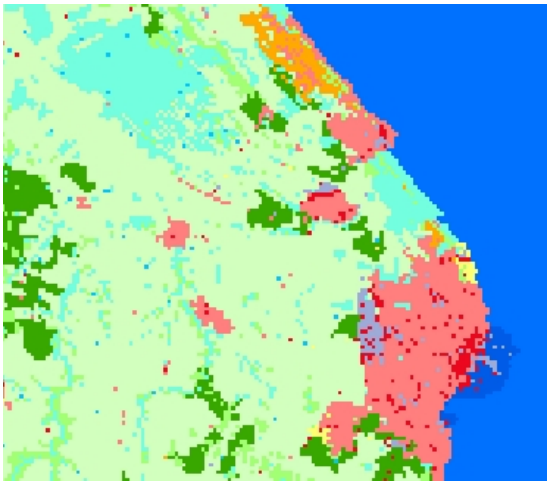


Figure 4. Land-use (simulated) in part of Northern Jutland in 2025.

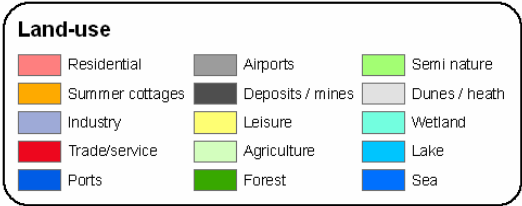


Figure 5. Land-use legend.

The simulation of the afforestation process takes outset in the following assumptions. New forests will expand from existing forests if possible; otherwise new forests will expand from random seed points within the areas designated as new forest areas. The figures 3 and 4 illustrate land-use for the base year 2005 and the simulated land-use for year 2025 using the driving forces mentioned above.

5 Concluding remarks

The European territory goes through a critical period with high pressure on nature and environment. In order to mitigate the negative consequences of this development the European Union has defined a set of recommendations for spatial development like the European Spatial Development Perspective [1] and Integrated Coastal Zone Management [2]. The use of spatial models and scenarios are often mentioned as important instruments in the strategy towards a sustainable development. Therefore we decided to develop a land-use simulation model aiming at supporting the decision making process here under public participation. Models are useful for unravel the complex collection of socio-economic and biophysical forces that determine the rate and spatial pattern of land use change and for estimating the impacts of land use changes.

The so-called LUCIA model is built as a user-friendly simulation framework - facilitating an easy adaptation to various requirements from planners, politicians and the public. The described cell-based approach with dual level driving forces has demonstrated its ability to make rather good simulations of the observed land-use pattern for the calibration year (2000). Furthermore, it is easy to make scenarios by for example changing the planning zones.

Currently, preparing input maps and visualising output maps are carried out in ArcGIS or similar software, but we are considering developing visualisation tools as an integrated part of the LUCIA modelling framework, but the easy data exchange with commercial GIS products like ArcGIS will be maintained.

The model has been tested on Danish data, but the next steps will be to use LUCIA in a transnational land-use modelling effort covering the whole Skagerrak region – i.e. the Skagerrak coast of Norway and the Swedish west coast north of Gothenburg. This will be a challenge due to the different availability of data sources and lack of syntactic and semantic interoperability.

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